Eur J Appl Physiol (2004) 92: 654–657
DOI 10.1007/s00421-004-1131-4

ORIGINAL ARTICLE

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On the use of porous materials to simulate evaporation in the human sweating process

Accepted: 9 January 2004 / Published online: 1 July 2004

Abstract The specific properties of porous materials when wet, namely the cooling effect near the surface due to the heat extraction during water evaporation, were known and used by ancient civilisations. During human perspiration, the necessary heat for sweat evaporation is provided by the cutaneous surface, which induces a temperature drop similar to that observed in a wet porous material. The potential for using porous materials to simulate human perspiration was investigated in this work using different permanently saturated porous materials (plaster, white clay and red clay). The existence and duration of a constant drying rate was studied, as well its dependency on the surrounding conditions, namely temperature, moisture and velocity. We verified the existence of a period with constant drying rate for all the tested samples; this is evidence that a uniformly distributed humid layer is formed and stays on the external surface of the porous body. This represents a step forward in simulation of the sweating mechanism. All three tested porous materials showed very good reproducibility and good sensitivity in terms of the response of the evaporation rate to any variation of the relative humidity.

Keywords Thermal comfort · Porous material · Perspiration · Heat and mass transfer

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Introduction

Evaluation of the thermal environment currently plays a major role in people's lives because of their daily pressing demands and their individual and collective conscience regarding the efficient management of energy resources.

In heat stress situations, especially, the sweating mechanism plays a role in the thermal regulation of the human body. This physiological reaction occurs to keep the body's thermal balance in equilibrium without the occurrence of a dangerous increase in deep body temperature.

During evaporation of the sweat formed on the external surface of the human body, the amount of energy used up in the phase change that occurs when this biological fluid is removed induces a cooling effect. The same effect occurs in a hollow vessel with porous walls. If the hollow vessel is filled with water and the permeability of its walls is within the appropriate range, it is possible to create a uniform humidified layer on the external surface. This method offers a good possibility for simulating the human sweating mechanism and quantifying of the effect of latent heat losses on the human thermal balance for a given environment.

Analysis of the literature on this subject reveals the difficulties in realistically simulating the various thermal regulation mechanisms of the human body. The main published work (Frankenberger et al. 1997) reports on sweating, namely on the achievement of a uniformly distributed humid layer over the whole external surface of the body; in order to do this a mannequin with an external layer of porous clay was developed. The main criticisms of the work related to the fact that there was an overestimation of the cooling effect relative to that which actually occurs in the human body. Nevins and Darwish (1970) used the cooling effect theory, which is applicable to the case of porous materials, to describe the diffusion of metabolic heat through human tissues. They formulated a mathematical model for the behaviour of the thermal regulation mechanism applied specifically to the human head. Recently, Bruhwiler (2003) used the injection of water vapour in circles of cotton tissue to simulate the sweating of a mannequin's head in studies of helmets for motorcyclists. This is acceptable for studying the properties of the helmet, but regarding the thermal balance of the head itself, the cooling effect of phase change is not taken into account.

In the present work, we aimed to develop a thermal environment meter, which simultaneously sensed the different phenomena that affect human thermal balance, using different porous materials to evaluate its suitability to simulate the sweating mechanism in a small heated sensor or a thermal mannequin.

Methods

Exploratory tests were performed with different materials. First, cylindrical plaster proving specimens with typical dimensions of 30 cm length, 7.2 cm diameter and wall thickness between 4.5 and 10 mm were tested. Other specimens made of red and white clay with fixed-wall thickness were also tested.

The method of assuring that the porous walls were saturated with water varied depending on the material. Thus, for white and red clay specimens, the inner volume of the cylinder was initially filled with water. We verified that saturation on the walls lasted the length of the experimental period, independently of the decreasing water level inside the cylinder. In the case of the plaster samples, this method was not suitable because the permeability of the plaster was too high and the water saturation level dropped on the external surface of the proving specimen. Water that leaves the body of the cylinder without being evaporated does not contribute to the cooling effect and introduces difficulties in quantifying the thermal losses of the proving sample. In fact the same phenomenon can occur with the human body when it is subjected to a high metabolic rate in warm and humid climates, when sweat dropping represents a loss of efficiency of the cooling effect. To overcome this difficulty with plaster specimens, their inner volume was completely filled with absorbent cotton wool saturated with water. This method provided complete humidification of the solid walls of the plaster-proving sample, even during tests that lasted for a few hours.

Experimental technique

Tests were carried out inside a small climatic chamber. Temperatures higher then the ambient temperature were achieved by introducing an electrical heater, while an air-conditioning unit was used as both a humidifier and a dehumidifier. Air temperature and relative humidity inside the chamber was monitored with a Rotronic Hygromer probe, and a digital precision balance connected to a computer was used to determine the loss of weight by evaporation of the tested specimens.

Results

In Fig. 1, the changes in weight of samples made of different materials (red clay, white clay and plaster) are depicted over the test period. The three tests were performed for different combinations of air temperature and relative humidity, but it was possible, in all three, to identify a period of time when the variation in weight was linear.

The differences in behaviour were due, not only to the different characteristics of the materials and geometry of tested samples, but also to the different environmental conditions. Results in Fig. 1 refer only to the steady-state period of the tests. The initial transient phase, when the temperature adjustment of the tested sample occurs, which typically lasts for 10 min, was omitted.

With the aim of studying the influence of the wall thickness on the evaporation rate, three proving specimens made of plaster with the same composition and thicknesses of 10 mm (GS1), 5 mm (GS2) and 4.5 mm (GS3) were tested (Table 1). The analysis indicates that there was no difference in terms of the steady-state evaporation rate; the only influence detected was that of the difference in the duration of the initial transient phase, which was longer for thicker samples.

From data collected during the tests, it was possible to verify a good agreement between the wall temperature of tested specimens and the wet bulb temperature of the surrounding environment determined through the psychometric chart of air (Cengel and Boles 1994).

Results from sensitivity tests carried out with a plaster sample that was subjected to various air temperature and relative humidity conditions are presented in Figs. 2, 3 and 4. The evaporation or drying rate, S_w, is

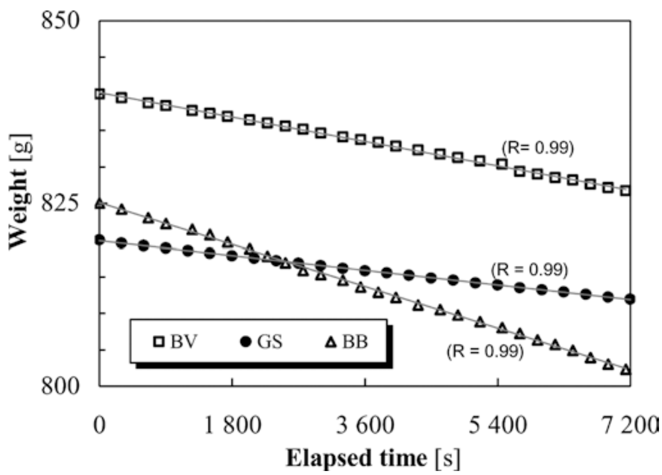

Fig. 1 Change in weight over time for red clay (*BV*), white clay (*BB*) and plaster (*GS*) samples

Table 1 Materials and environmental conditions for tests presented in Fig. 1. T_aAir temperature [mean (SEM)], HR relative humidity

Material	Surface area(m^2)	T_a(°C)	HR(%)
Red clay	0.0665	19 (1)	55
White clay	0.0396	17 (1)	60
Plaster	0.0633	20 (1)	55

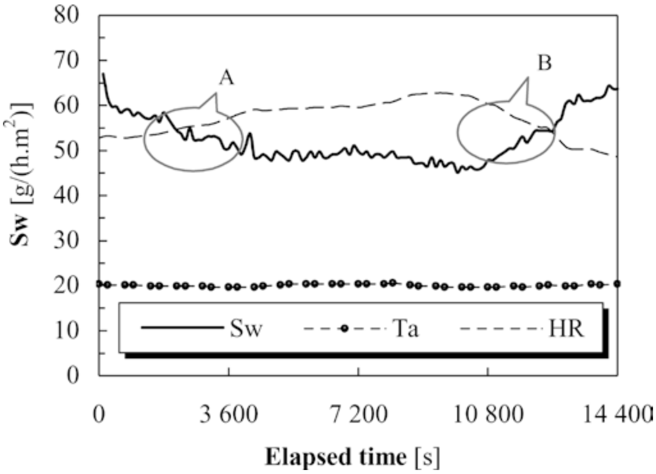

Fig. 2 Change in evaporation rate (S_w) for non-constant humidity conditions (for GS). T_a Air temperature, *HR* relative humidity

computed from the constant negative slope of the respective time period and it is expressed in grams per square metre per hour; the following expression is used for its calculation:

$$S_w = 3.6 \times 10^6 \frac{\Delta P}{A_s \Delta t}$$

where ΔP is the weight loss (kilograms) verified for the time interval Δt (seconds), and A_s (square metres) is the external surface area of the specimen tested.

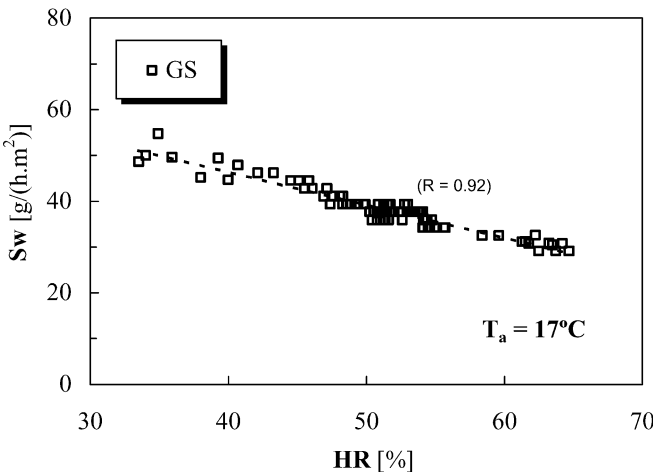

Fig. 3 S_w versus HR for a plaster specimen

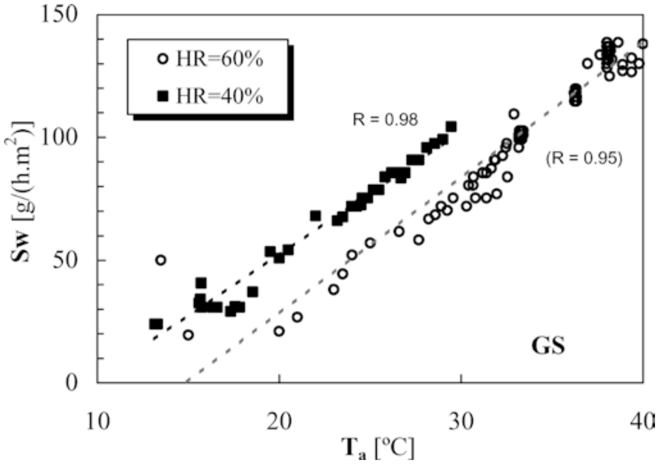

Fig. 4 S_w versus T_a for a plaster specimen

In Fig. 2, there is good reproducibility of results, while in Figs. 3 and 4, respectively, variations in sensitivity to humidity and temperature are evident.

Discussion

The existence of a period with constant drying rate for all the tested samples was verified in this study. This has previously been referred to by various authors (Chen and Pei 1989; Harmathy 1969; Nasrallah and Perre 1988; Nevins and Darwish 1970) as evidence that a uniformly distributed humid layer is formed and stays on the external surface of the porous body. This represents a step forward in the simulation of the sweating mechanism.

We detected no influence of wall thickness on the evaporation rate in steady-state conditions. Only the duration of the initial transient phase was influenced by this parameter.

All the three tested porous materials presented very good reproducibility and good sensitivity in terms of the response of the evaporation rate to any variation of the relative humidity; this environmental parameter is fundamental when processes of latent heat loss are involved. The selection of a material to manufacture probes for a thermal environment meter should be based upon parameters such as mechanical stability, possibility of porosity regulation and long-term usage.

Acknowledgements The first author acknowledges a grant from the European Programme PRODEP, which supported his doctoral project.

References

Bruhwiler PA (2003) Heated, perspiring manikin headform for the measurement of headgear ventilation characteristics. Meas Sci Technol 14:217–227

Cengel YA, Boles MA (1994) Thermodynamics–an engineering approach, 2nd edn. McGraw-Hill, New York

Chen P, Pei CT (1989) A mathematical model of drying processes. Int J Heat Mass Transfer 32:297–310

Frankenberger RT, Nahim W, Konecny E (1997) Development of a premature baby simulator. World Congress on Medical Physics and Biomedical Engineering, Nice, France.

Harmathy TZ (1969) Simultaneous moisture and heat transfer in porous systems with particular reference to drying. Ind Eng Chem Fundam 8:92–103

Nasrallah SB, Perre P (1988) Detailed study of model of heat and mass transfer during convective drying of porous media. Int J Heat Mass Transfer 31:957–967

Nevins RG, Darwish MA (1970) Heat transfer through subcutaneous tissue as heat generating porous material. In: Hardy JD, Gagge AP, Stolwijk JA (eds) Physiological and behavioral temperature regulation. Thomas, Springfield, Ill., pp 281–301